Estimation of Building Parameters Using Simplified Energy Balance Model and Metered Whole Building Energy Use

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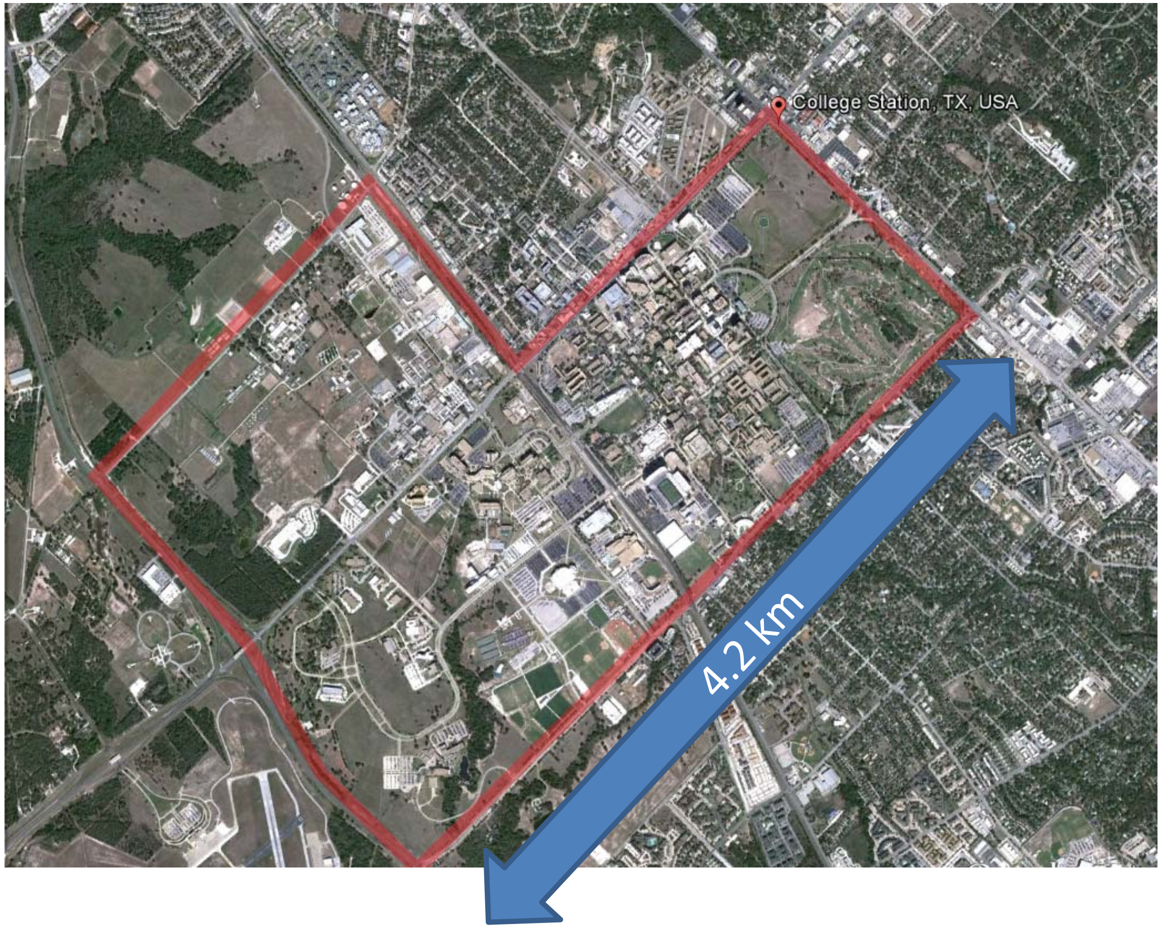


Texas A&M University, College Station, TX, USA

Manchester, UK

Background

Energy use analysis for Texas A&M University campus buildings

- Assessment of daily data from 520 energy meters for electricity, chilled water, and heating water in 171 buildings (16,000,000 ft^2 or 1,500,000 m^2) every month
  - Anomaly detection, imputation of missing data, estimation of appropriate consumption for unreliable meters
    - Billing information for utilities department
  - Monitoring changes in the consumption patterns and levels
    - Track energy performance after energy retrofit
    - Detect opportunities for energy use optimization

Background

- Energy balance variable (Shao and Claridge, 2006)
  - Applications for energy data analysis (Baltazar et al., 2007 and 2012)

Whole building control volume

$$\Delta E_{CV} = E_{entering} - E_{leaving}$$
$$= Q_{air} + Q_{cond} + Q_{sol} + Q_{occ} + \underbrace{Q_E - E_C + E_H}_{\text{Measurable}}$$

Heating energy use

Cooling energy use

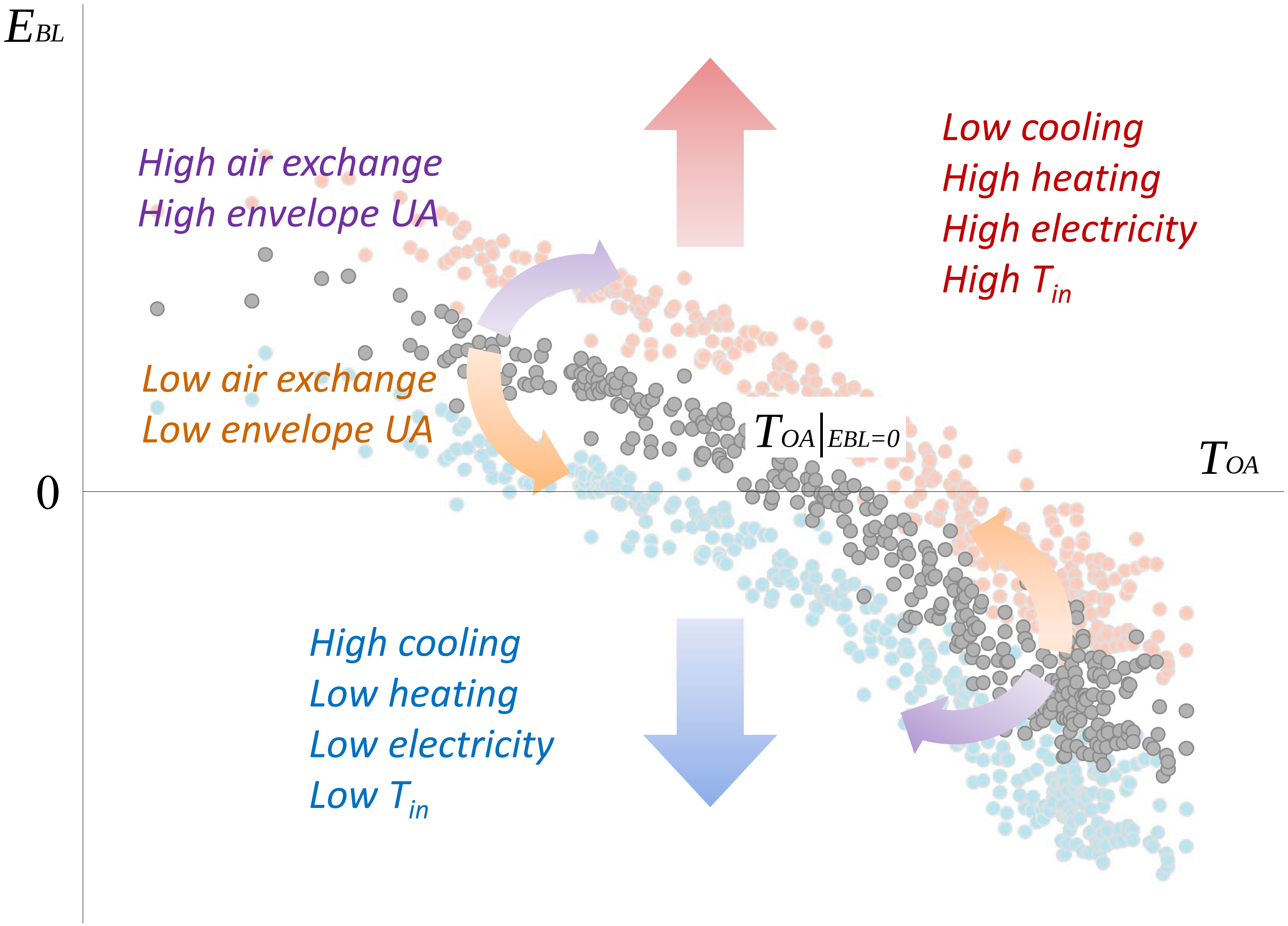
Heat load from electricity use

Steady state $\Delta E_{CV} = 0$

$$E_{BL} = Q_E - E_C + E_H$$
$$= fE_E - E_C + E_H$$
$$= -Q_{air} - Q_{cond} - Q_{sol} - Q_{occ}$$

Indirect measurement of the aggregate load

Interpretation of Energy Balance



Motivation

- Quantify the interpretation of Energy Balance
  - Air exchange rates and overall heat loss coefficient of the building envelope have significant influences on the heating and cooling loads.
  - Direct measurement of those parameters in operating buildings requires considerable time and labor.
  - Obtained parameters can be used for building energy optimization.
  - Data validation technique can be refined.

Earlier studies on building parameter estimation (steady-state)

- Rabl and Rialhe (1992)
  - Cooling and heating energy consumption is separately analyzed.
  - Misleading parameter estimates for commercial buildings with simultaneous cooling and heating
- Reddy et al. (1994)
  - Building thermal load (Q_B)

    Q_B = cooling energy use – heating energy use
- Deng (1997)
  - Estimation of overall heat loss coefficient and ventilation parameter using the Q_B variable
  - Synthetic simulation energy use data with constant building parameters
  - The parameter estimates are found to be accurate when daily data over the entire year are used.

This study

- Develops steady-state models and expression of key parameters for E_{BL}. Revisits Q_B model expressions based on the whole building energy balance.
- Compares parameter estimations using E_{BL} models and Q_B models.
- Non-ideal case is also tested.
- Proposes a reference temperature parameter T_{in}* as a measure to check unbalanced cooling and heating consumption or unreliable models.

Methodology

- Develop regression models
  - Simplified steady-state models for the E_{BL} and Q_B variables
  - Mathematical expressions of key parameters
- Estimate and evaluate parameters using multiple linear regression analysis.
  - Simulation building
    - Data
      - Energy Plus simulation model for a large commercial building
    - Compare parameter estimates with simulation inputs
  - Actual buildings
    - Data
      - Measured OA volume air flow from 3 buildings
    - Compare parameter estimates with measured values

Models

Energy balance load (E_{BL})

Building thermal load (Q_B)

$$E_{BL} = E_E - E_C + E_H$$
$$= -Q_{air} - Q_{cond} - Q_{sol} - Q_{occ} + (1-f)E_E$$

$$Q_B = E_C - E_H$$
$$= Q_{air} + Q_{cond} + Q_{sol} + Q_{occ} + Q_E$$
$$= Q_{air} + Q_{cond} + Q_{sol} + Q_{occ} + fE_E$$

f = fraction of electricity use (E_E) which turns into the heat load ($0 \le f \le 1$)

Simplified steady-state loads

$$Q_{occ} + fE_E = E_{LE} k_s (1 + k_l X)$$

Deng (1997)

Air exchange $Q_{air} = m_v c_p (T_{oa} - T_{in}) + m_v h_v X (W_{oa} - W_{in})$

Conduction $Q_{cond} = UA_s (T_{oa} - T_{in})$

Solar $Q_{sol} = a_{sol} + b_{sol} T_{oa}$

$$= a'_{sol} + b_{sol}(T_{oa} - T_{in})$$

$$X = \begin{cases} 1 & (W_{oa} > W_{in}) \\ 0 & (\text{otherwise}) \end{cases}$$

$W_{in} \le 0.01$ kg/kg
$T_{in} =$ const.

Regression models

$$E_{BL} = \beta_0 + \beta_T T_{oa} + \beta_W X (W_{oa} - W_{in}) + \varepsilon$$

$$Q_B = \beta_0 + \beta_{sens} E_{LE} + \beta_{lat} X E_{LE} + \beta_T T_{oa} + \beta_W X (W_{oa} - W_{in}) + \varepsilon$$

Key Parameters

Regression models

$$E_{BL} = \beta_0 + \beta_T T_{oa} + \beta_W X(W_{oa} - W_{in}) + \varepsilon$$

$$Q_B = \beta_0 + \beta_{sens} E_{LE} + \beta_{lat} X E_{LE} + \beta_T T_{oa} + \beta_W X(W_{oa} - W_{in}) + \varepsilon$$

$$X = \begin{cases} 1 & (W_{oa} > W_{in}) \\ 0 & (\text{otherwise}) \end{cases}$$

	Building parameter	E_{BL}	Q_B
Air exchange rate	m_v	$-\hat{\beta}_W / h_v$	$\hat{\beta}_W / h_v$
Overall heat transfer coefficient	$U^* A_s$	$-\hat{\beta}_T + \hat{\beta}_W c_p / h_v$	$\hat{\beta}_T - \hat{\beta}_W c_p / h_v$
Reference temperature	T_{in}^*	$-\hat{\beta}_0 / \hat{\beta}_T$	$-\hat{\beta}_0 / \hat{\beta}_T$

Reference temperature T_{in}*is similar to the balance point temperature

E_{BL}

$$T_{in}{}^* = T_{in} - \frac{Q_{occ} + a'_{sol}}{UA_s + m_v c_p + b_{sol}}$$

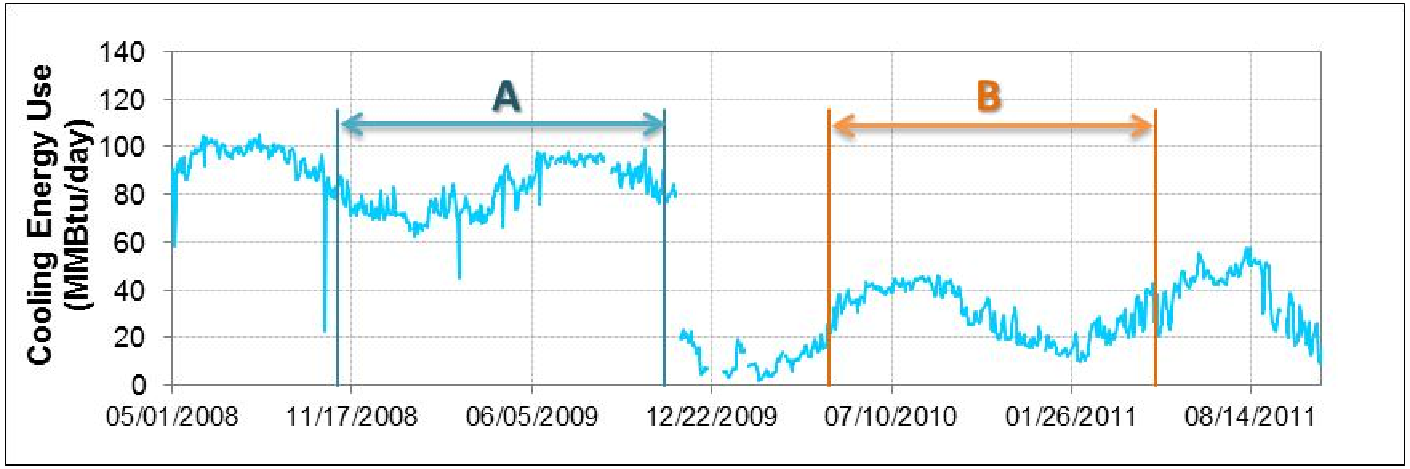
T_{in}* for E_{BL} is typically $2°C$ to $3°C$ below T_{in} (stable)

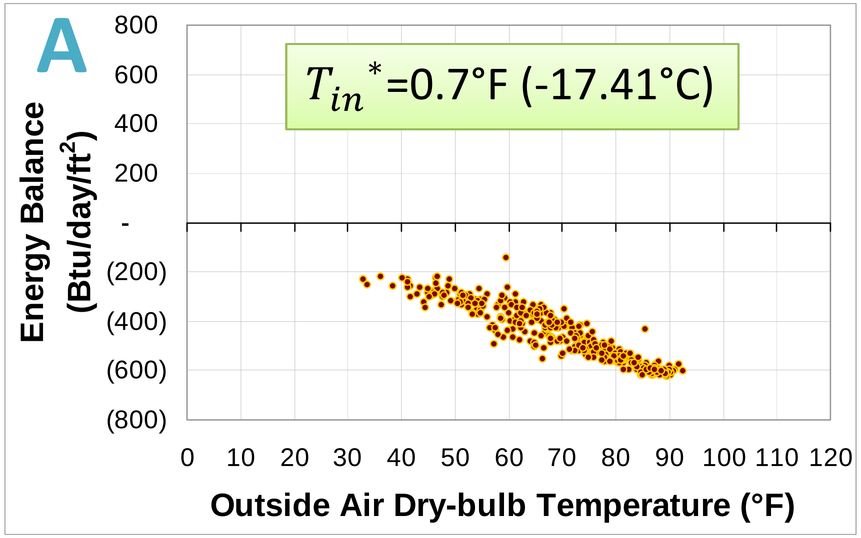
Q_B

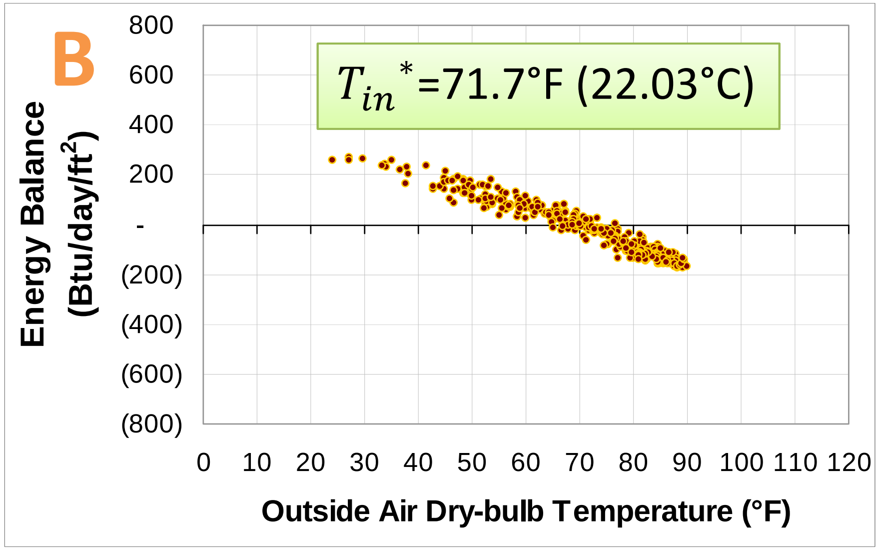
$$T_{in}{}^* = T_{in} - \frac{a'_{sol}}{UA_s + m_v c_p + b_{sol}}$$

T_{in}* for Q_B is around $1°C$ to $2°C$ below T_{in} (depends on the model fitting)

Example of the use of T_{in}*







Evaluation of Parameter Estimations

- Synthetic data from EnergyPlus building energy simulation
  - Results using daily data are shown here.
- Metered data from three campus buildings
  - Results from two buildings are shown here.

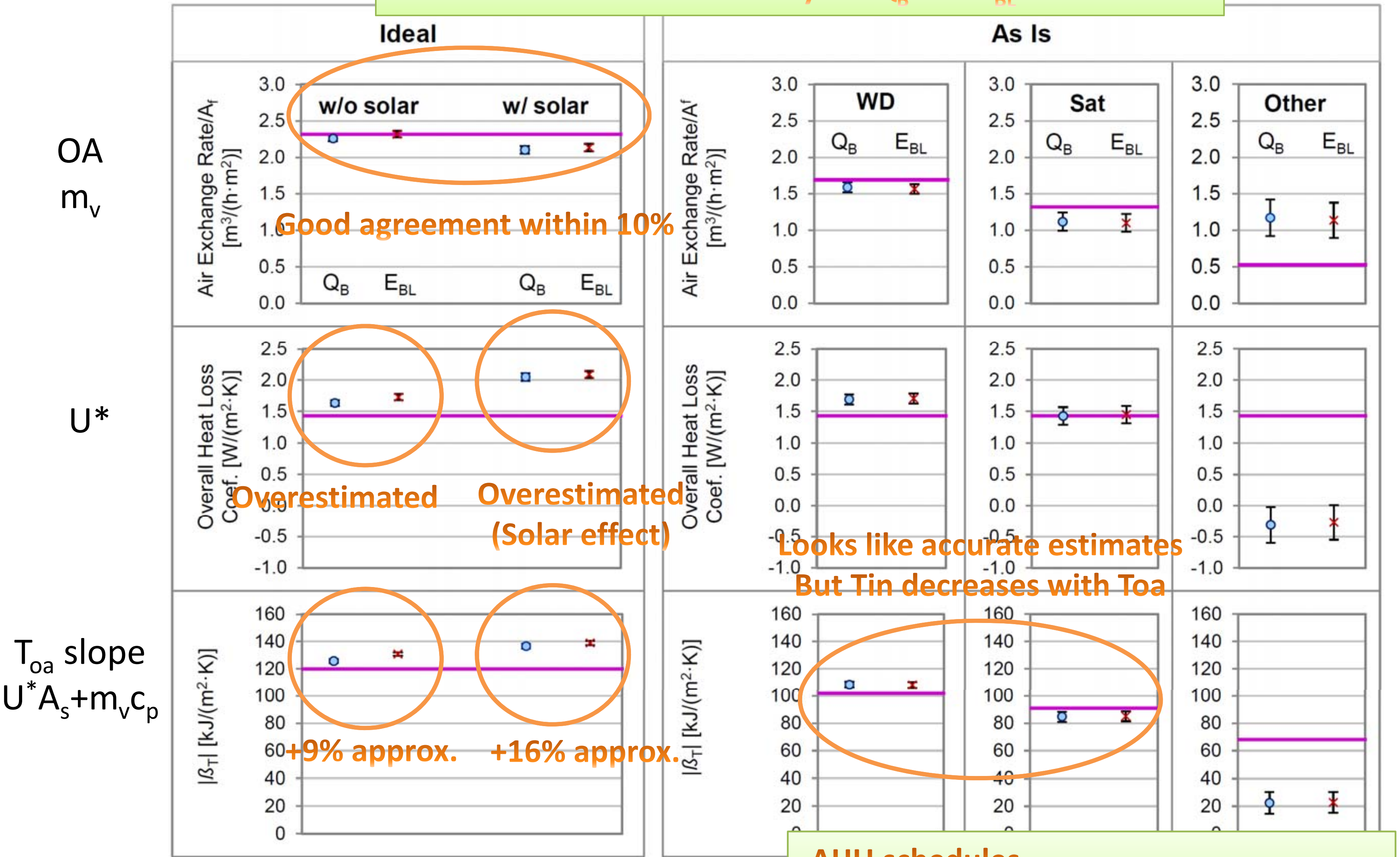
Energy use data from simulation - Data

Large commercial building in a hot and humid climate region

- The commercial reference building model for existing buildings constructed in or after 1980 in a hot and humid climate zone (DOE 2010)
- 12 stories above grade and a basement
- Total conditioned area of 46 320 m^2
- Single duct VAV systems with reheat terminals
- No economizer or heat recovery
- Houston, TX TMY 2 weather data
- Three runs
  - **As is**: Original input file with many sources of energy use variability. Three different schedules for Weekday (WD), Saturday (Sat), and Sunday and holidays (Other); HVAC on/off; T_{in} variations due to set point reset
  - **Ideal w/ solar**: Constant indoor temperature set point and ventilation, HVAC is on all the time, no infiltration.
  - **Ideal w/o solar**: same simulation model as above but solar irradiance of the weather file was set to zero.

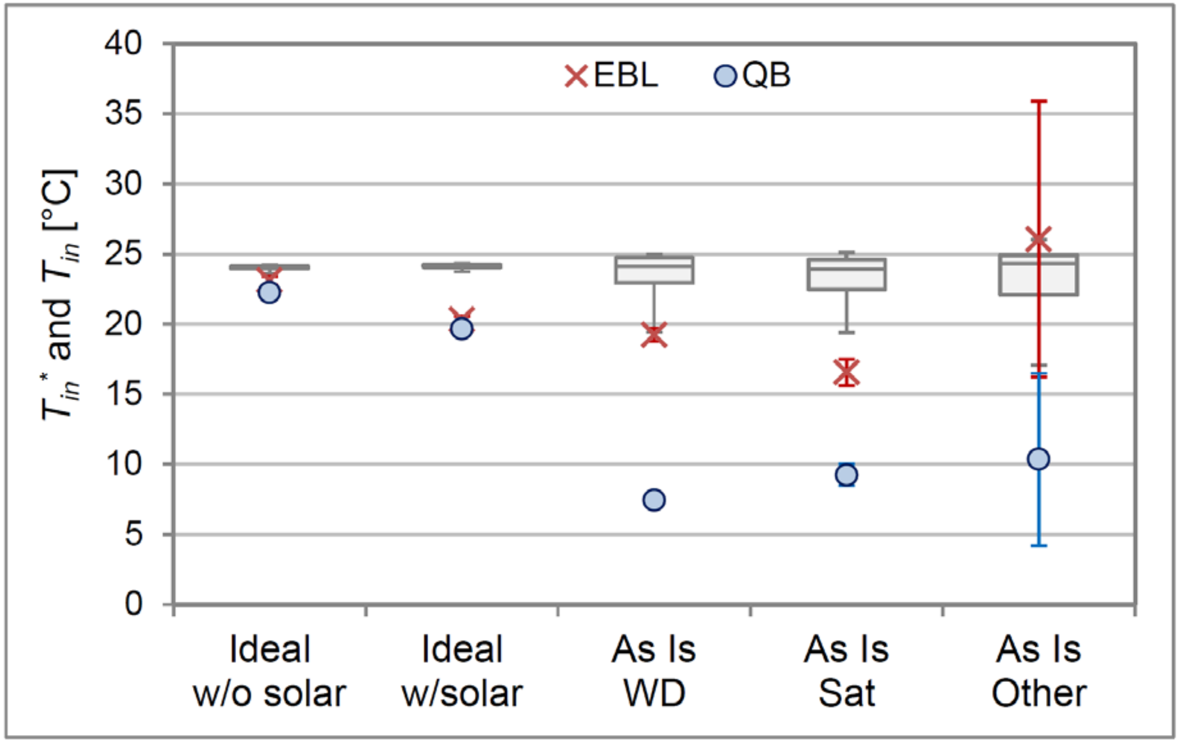
Energy use data from simulation – Results

Similar level of accuracy for Q_B and E_{BL} models



AHU schedules
19 hrs/day 12 hrs/day Off

Energy use data from simulation – Results Reference Temperature T_{in}*



E_{BL}

$$T_{in}{}^{*} = T_{in} - \frac{Q_{occ} + a'_{sol}}{UA_s + m_v c_p + b_{sol}}$$

Q_B

$$T_{in}{}^{*} = T_{in} - \frac{a'_{sol} + Q_{occ} + fE_E}{UA_s + m_v c_p + b_{sol}}$$

Energy use data from actual buildings

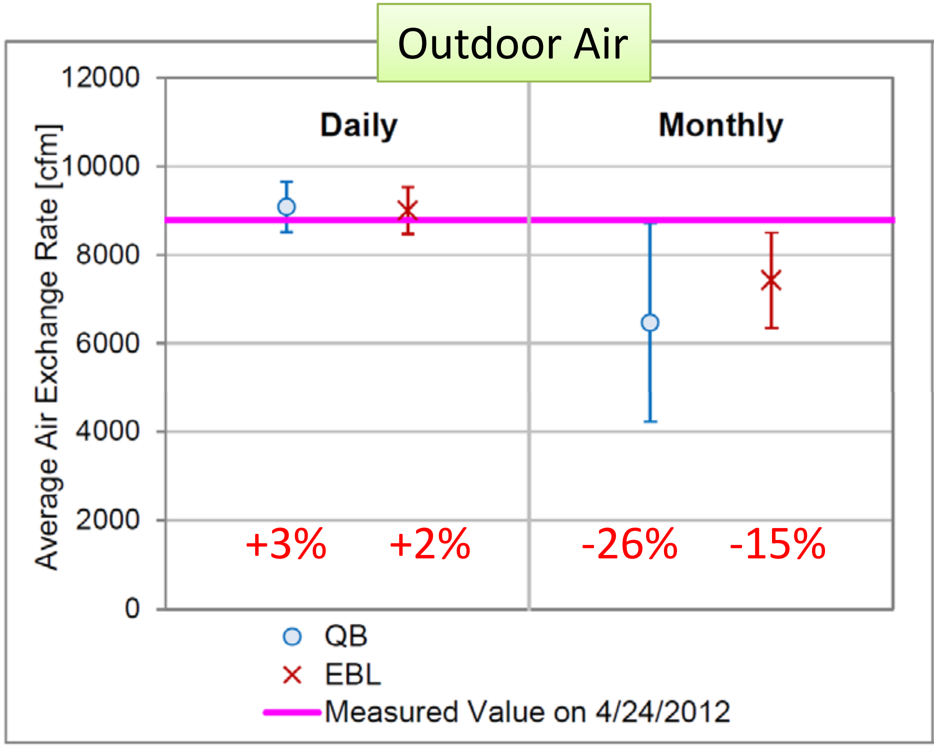
- Four-story dormitories (~6000 m^2)
- Similar design and dimensions built in 1979 and 1980.
- Dedicated outdoor air systems
  - OA flow rate was measured on 4/24/2012
- Local weather data
  - National Climatic Data Center
- Metered energy data

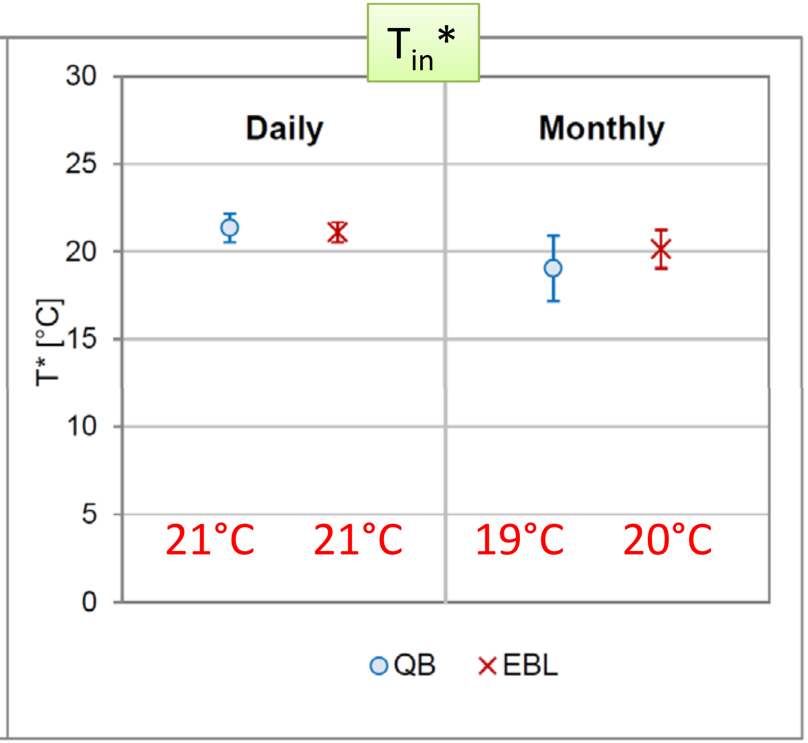
  Bldg HS: 7/1/2011–6/30/2012

  Bldg MF: 9/1/2011–6/30/2012

  Bldg HB: 7/21/2011–6/30/2012

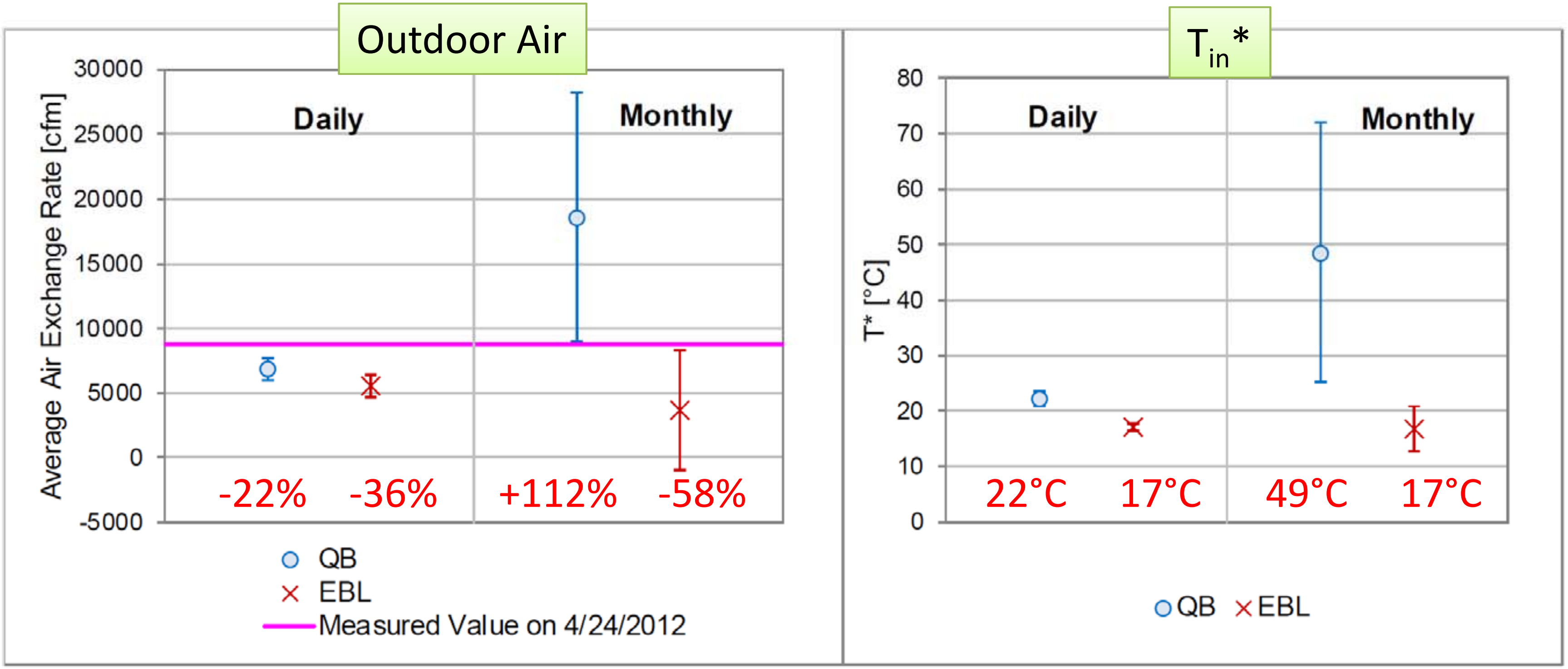
Energy use data from actual buildings-Results HS building





- Monthly data have stronger multicollinearity compared to daily data (VIF>10 for Q_B models and VIF>4 for E_{BL} models)

Energy use data from actual buildings-Results HB Building



- OA flow rate changed during the modeling period.
- Questionable reference temperature T_{in}*
- High collinearity between OA humidity and electricity variables in the Q_B monthly model. The effect of electricity variable is overestimated around 5 times as high as the normal level.

Summary and Future Studies

- Data-driven method to estimate influential building parameters using variables E_{BL} and Q_B have been presented.
- E_{BL} and Q_B models have a similar level of accuracy of the parameter estimates (daily synthetic data max. error: +10% for air exchange rate and -16% for T_{oa} slope), however, Q_B models require more careful selection of variables.
  - Latent portion of Q_{occ} doesn't have detectable relation with electricity use in real data.
  - Electricity variable is not suitable for grouped data by day types (small variability)
  - Electricity variable caused unexpected inflations of the estimates in the monthly data
- Parameters estimated under <u>mild</u> violations of model assumptions for the simulation data did not show serious errors.
  - 12 hrs/day HVAC operating hours
  - T_{in} set point reset (occupied/unoccupied hours, cooling/heating)
- A parameter T_{in}^* have introduced to detect problems in the metered energy data and model misspecifications.
- A dormitory building with stable parameters during the modeling period yielded +3% error (daily data) and -15% error (monthly data) in the air exchange rate estimates.
- How to set a reasonable range for T_{in}^*?
- Is this method applicable to dry weather?

Thank you

References

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Table 5: Data sets used in the analysis and the explanatory variable terms included in the regression models. The checked terms are included.

Dataset	Explanatory variable terms included in the regression models					
	E_{BL}		Q_B			
	T_{oa}	$X(W_{oa}-W_{in})$	T_{oa}	$X(W_{oa}-W_{in})$	E_{LE}	XE_{LE}
Daily interval						
Ideal w/ solar	✓	✓	✓	✓	✓	✓
Ideal w/o solar	✓	✓	✓	✓	✓	✓
As is (WD)	✓	✓	✓	✓		
As is (Sat)	✓	✓	✓	✓		
As is (Other)	✓	✓	✓	✓		
HS (Jul–Jun)	✓	✓	✓	✓	✓	
MF	✓	✓	✓	✓	✓	
HB	✓	✓	✓	✓	✓	
Monthly interval						
Ideal w/ solar	✓	✓	✓	✓	✓	
Ideal w/o solar	✓	✓	✓	✓	✓	
As is	✓	✓	✓	✓	✓	
HS (Jul–Jun)	✓	✓	✓	✓	✓	
MF	✓	✓	✓	✓	✓	
HB	✓	✓	✓	✓	✓	

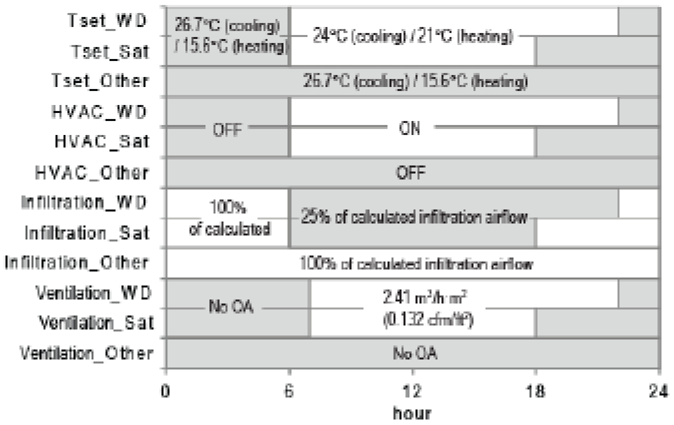

Fig. 1. System schedules for the as-is case

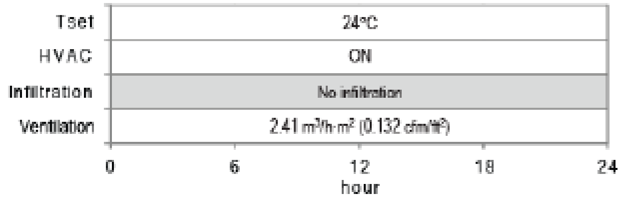

Fig. 2. System schedules for the ideal cases

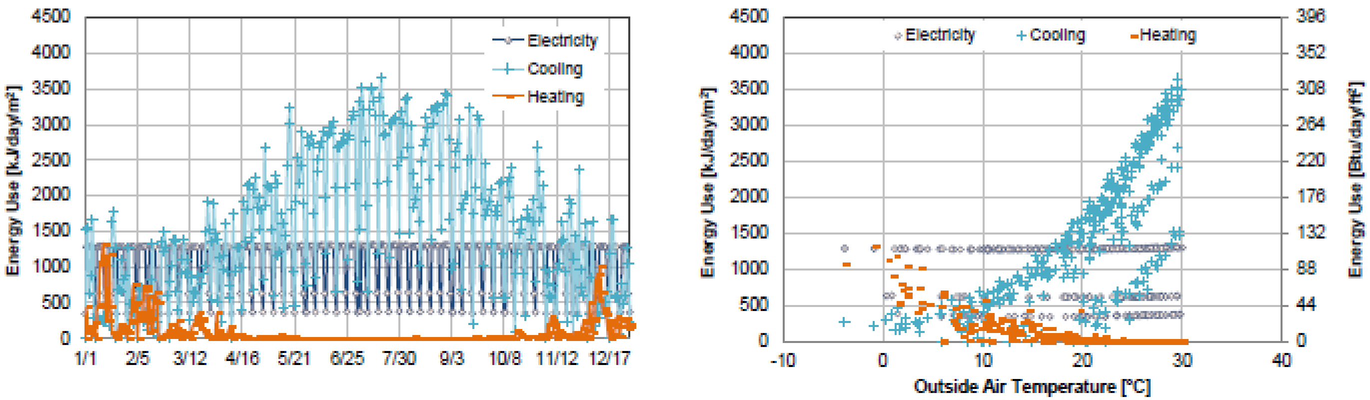

Fig. 3. Whole building daily energy uses for electricity, cooling, and heating per unit conditioned floor area for the as-is case. Time series plot is in the left and scatter plot versus daily average outside air temperature is in the right.

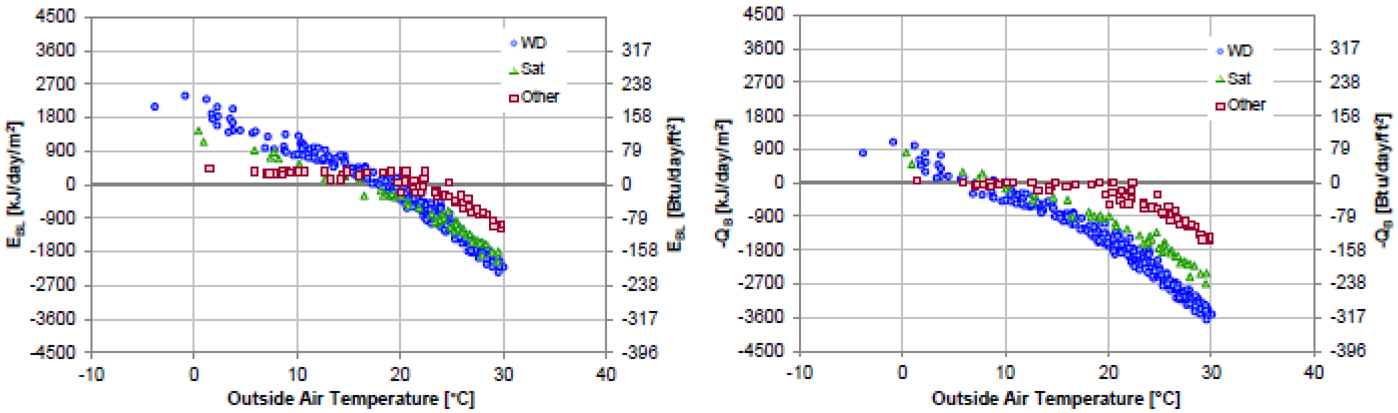

Fig. 4. E_{BL} and Q_B per unit conditioned floor area in the as-is case plotted versus daily average outside air temperature

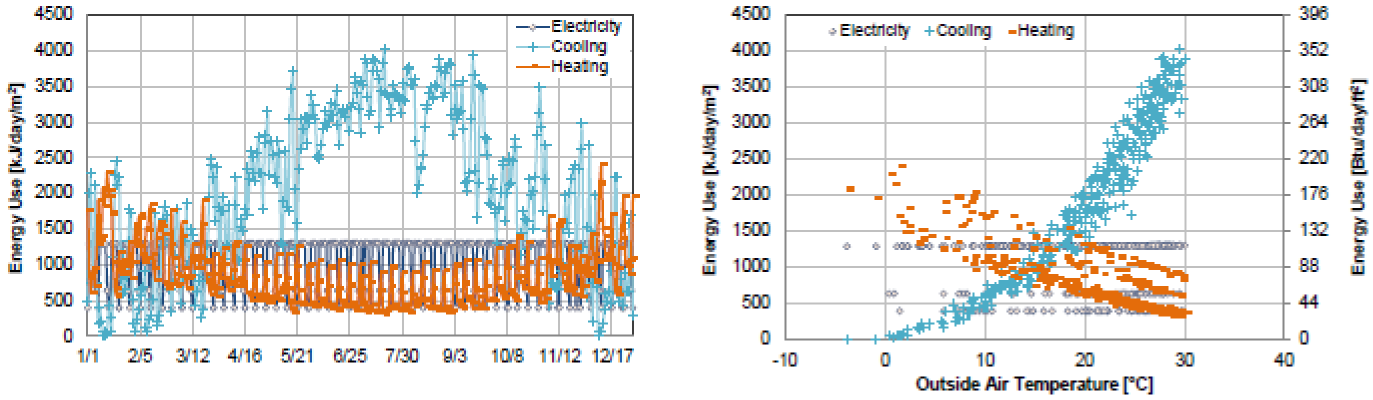

Fig. 5. Whole building daily energy uses for electricity, cooling, and heating per unit conditioned floor area for the ideal w/o solar case. Time series plot is in the left and scatter plot versus daily average outside air temperature is in the right.

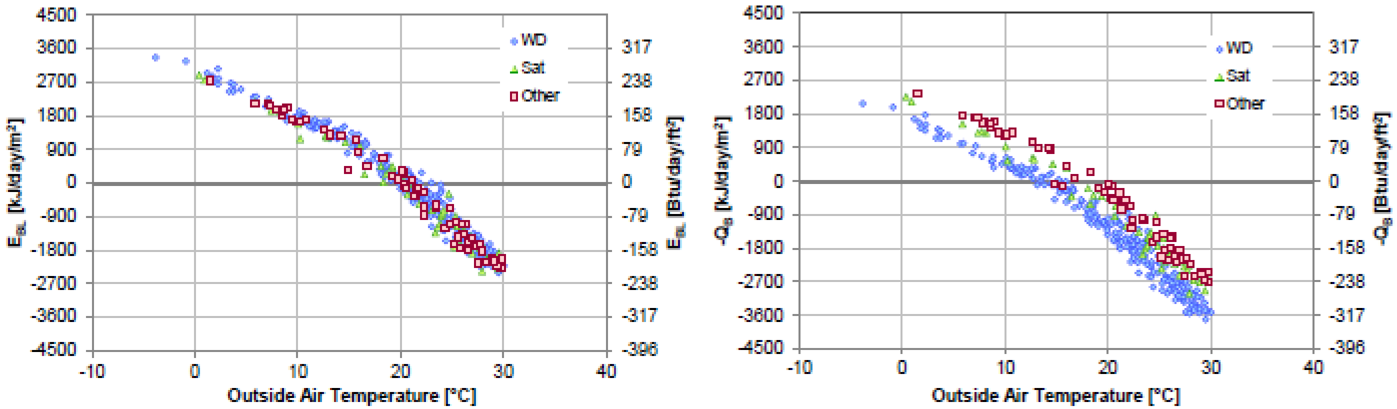

Fig. 6. E_{BL} and Q_B per unit conditioned floor area in the ideal w/o solar case plotted versus daily average outside air temperature.

$$\mathrm{VIF} = \frac{1}{1-\mathrm{R}_i^2} \qquad (12)$$

where R_i^2 is the multiple coefficient of determination between the *i*-th explanatory variable and all of the other explanatory variables in the regression equation. The exact value of VIF at which muticolinearity is declared depends on the individual investigator. Some use a value of 5 and others 10 (Haan, 2002).

Explanatory variable	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily WD	Daily Sat	Daily Other
T_{oa}	4.02	15.63	3.07	8.34	3.07	7.59	2.96	2.95	3.77
$X(W_{oa}-W_{in})$	3.15	8.12	3.08	7.94	3.07	7.59	2.96	2.95	3.77
E_{LR}	1.55	1.28	1.00	1.14					
XE_{LR}	2.97	5.97							

Explanatory variable	HS				MF				HB			
	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly
T_{oa}	2.95	14.53	2.86	4.25	2.17	5.23	2.13	2.48	2.72	11.39	2.66	4.01
$X(W_{oa}-W_{in})$	3.16	15.28	2.86	4.25	2.33	5.52	2.13	2.48	2.96	21.51	2.66	4.01
E_E	1.13	3.69			1.11	2.33			1.15	6.19		